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Corresponding Author: Andrew Whelton, Professor, Lyles School of Civil Engineering, Division of Ecological and Environmental Engineering, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907-2051. Email: awhelton@purdue.edu

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Supplementary File

Bystander Chemical Exposures and Injuries Associated with Nearby Plastic Sewer Pipe Manufacture: Public Health Practice and Lessons

SI-1. Chain of events pertaining to CIPP installation, government agencies, and research

1971, Cured-in-place-pipe (CIPP) technology was invented in England to repair buried sewer pipes. This practice involves the chemical manufacture of a new plastic pipe inside an existing damaged pipe using raw resin and a curing process to harden the raw materials into a plastic.

1975, CIPP technology arrived in the US.

1977, The CIPP US patent was approved and a single CIPP company formed in the US called Insituform.

1994, The CIPP US patent expired and other CIPP companies were formed in the US.

2001, An air testing study was conducted in Toronto, Canada and today is still erroneously invoked by the CIPP industry, engineering consultants, first responders and municipalities (who are given information by the CIPP industry). Limited air testing for this study found a maximum of 3.2 ppm styrene vapor at a worksite. Details about the sampling and curing process, underground transport of vapors, etc. were lacking.

2002, Two CIPP workers died and five CIPP workers were hospitalized at a worksite in Iowa due to their exposure to "inhalation hazards such as hydrogen sulfide, unknown gases, and an oxygen-deficient atmosphere." Workers were overcome by the hazardous atmosphere and were asphyxiated (Investigation 115096976). A CIPP company was issued multiple citations and penalties by Iowa OSHA.

2005, The ATSDR issued (Agency for Toxic Substances and Disease Registry, 2005) a health consultation report for a CIPP sewer pipe repair caused office building volatile organic compound (VOC) contamination incident in Milwaukee, Wisconsin. The incident caused multiple building evacuations and created a 'public health hazard' for the workers over several months after the CIPP project was completed.

2006, The Netherlands National Institute for Public Health and the Environment (RIVM, 2006) conducted air testing at a CIPP worksite and reported styrene emission.

2013, The Commonwealth Court of Pennsylvania (Commonwealth Court of Pennsylvania, 2018) records show that a CIPP worker lost consciousness inside an uncured resin tube, was exposed to the CIPP resin chemicals, and was pulled from the tube using a rope on his ankles. The claimant sought emergency medical care and worker's compensation.

2013, The Public Health England (Public Health England, 2013) raised chemical hazards and poisons issue for CIPP

2014, A Purdue University and University of South Alabama team published (Tabor et al., 2014) a peer-reviewed field study showing that the condensed, concentrated liquid material (condensate) left behind after steam curing of a CIPP contained approximately 15,300 ppm styrene among other VOCs and SVOCs. Aquatic toxicity testing indicated that the liquid, at room temperature, dissolved *Daphnia magna* freshwater organisms in less than 24 hours. Since 2001, the CIPP industry group had recommended contractors dispose of this chemical waste into "streams and ditches", though that action would seemingly violate the Clean Water Act.

2016, A University of New Orleans graduate student hired a commercial laboratory to conduct CIPP worksite air analysis as part of her dissertation research in Los Angeles (Ajdari, 2016). At the time she was also an engineering intern at the Bureau of Engineering, City of Los Angeles and her dissertation work focused on environmental impacts of CIPP technology. She found that during CIPP curing with steam and during the CIPP cool down process with air, styrene vapor levels ranged from 3.62 to 76.7 ppm and 250 to 1,070 ppm, respectively. Some levels found exceeded the NIOSH immediately dangerous to life and health (IDLH) styrene limit of 700 ppm. Workers were also observed residing inside the exhaust waste chemical plumes without dermal or respiratory protection.

2016, In Kansas, a CIPP worker claimed he was injured during manual labor activities and sought worker's compensation (United States District Court, D. Kansas., 2018).

2017, The California Department of Health issued (California Department of Public Health, 2017) a statewide "Safety Alert" about the CIPP sewer pipe repair practice, identified concerns about chemical waste discharge, and human exposure and health impacts after a building chemical contamination incident. Their document was revised and reissued in 2020 (see below).

2017, A Purdue University team published (Teimouri Sendesi et al., 2017) a peer-reviewed field study showing what CIPP companies called "steam" was not steam, but instead a multi-phase mixture of partially cured resin, particulates, organic vapors, and water vapor. When the whole emission was captured and cooled to room temperature, the phases separated further showing the complexity of what workers were exposed to. This sampling approach was not possible with typical sorbent tubes, canisters, or Tedlar bags commonly used to look for "vapors" only. Also found was that more than styrene vapor was detected in multi-phase mixture to include benzaldehyde, dibutyl phthalate, phenol and other chemicals. Styrene levels ranged from 1,800 to 4,100 ppm in the multi-phase mixture samples. This multi-phase waste prompted death for acutely exposed mouse lung cells. Further, 59 chemical exposure events (Supporting Information file) were found reported for nearby office, restaurant, retail, school, daycare, university, and municipal buildings.

2017, The National Environmental Health Association (NEHA) hosted a webinar with the Purdue University team and NIOSH about CIPP chemical exposure risks and worker safety resources.

2018, The California Department of Public Health (California Department of Public Health, 2018) raised concerns about chemical intrusion into nearby residential buildings and issued issuing "CIPP Safety Alert"

2018, Toxicology researchers in France published (Persoons et al., 2018) a peer-reviewed field study showing that biomonitoring revealed elevated levels of styrene for CIPP workers.

2018, The Purdue University team published (Ra et al., 2018) a peer-reviewed study indicating that new chemicals can be created and emitted into the environment during CIPP manufacture that are not listed as ingredients on material safety data sheets (SDS). Some of these byproducts created here had been previously reported in waste discharged from previous CIPP worksites. Compounds reported included endocrine disrupting compounds, carcinogens, hazardous air pollutants and compounds with limited toxicological data.

2018, The OSHA Region 5 issued (Occupational Safety and Health Administration, 2018) a penalty to one CIPP company involved in the death of 22-year-old CIPP worker Brett Morrow in Streamwood, Illinois.

2019, The Purdue University team published (Ra et al., 2019) a peer-reviewed field study showing multiple HAPs, known and suspected carcinogens were emitted into the air for styrene- and nonstyrene- CIPP resins. Methylene chloride (> 1.5 ppm) and styrene (> 86 ppm) were quantified, but levels were likely much higher than reported. Numerous chemicals discharged into the air (including methylene chloride) were not listed on the material safety data sheets. A calibrated handheld photoionization detector (PID) did not accurately represent styrene air concentration when compared against whole air sampling. Levels differed between the PID and GC/MS analytical quantification method sometimes by 10s- to 1000s-fold likely due to the PID being overloaded with the multitude of organic vapors in the hazardous atmosphere. Particulates were generated when CIPP workers mechanically cut the cured plastic pipe. In the 44 newly reported chemical exposure events (Supporting Information file) was an incident in a U.S. Forest Service building, as well as in retail, office, municipal school, and hospital buildings, and evidence of a chemical exposure incident as far back as 1993 in Austin, TX.

2019, The Purdue University team published (Li et al., 2019) a peer-reviewed field study for ultraviolet light glass fiber CIPP where numerous chemicals not listed on the material safety data sheet (SDS) for the resin were found in the resins and discharged to the environment. The uncured resin tube contained 2.8 to 13.2 wt% VOC. Some chemicals include phthalic anhydride, maleic anhydride, styrene, styrene oxide, ethylbenzene, dibutyl phthalate, and others. It was also reported that the newly created CIPP contained 1.0 to 6.8 wt% VOC. Particulates were generated when CIPP workers mechanically cut the cured plastic pipe.

2019, The Purdue University team published (Kobos et al., 2019) a peer-reviewed study describing the inhalation toxicity of CIPP waste (captured at field sites) to mouse alveolar epithelial and alveolar macrophage cell lines. When styrene concentration was normalized across all exposures, cytotoxicity differences were observed between worksite samples. Protein changes were also related to pathways involved in cell damage, immune response, and cancer. Results demonstrated that exposure assessment of CIPP worksites should examine multiple chemical components beyond styrene, as many cellular responses were styrene-independent.

2019, The NIOSH published (National Institute for Occupational Safety and Health, 2019) their Health Hazard Evaluation report for a CIPP company (that used the ultraviolet light curing process, the least popular UV curing approach as of 2019). Results showed worker exposure to styrene during grinding a cured pipe (140 ppm) exceeded the 15-minute short-term exposure limit of 100 ppm when a manhole ventilator blower fan was not used. The next highest exposure to styrene occurred during cutting and taping of the liner (51 ppm) when the manhole ventilator blower fan was not used. Styrene was emitted from the new plastic after it was manufactured. Divinylbenzene was also found (so styrene was not the only chemical emitted into the air). When a sample of the uncured resin liner was placed in a glass vial, after 24 hours at room temperature the styrene air concentration in the closed vial was found to be 1,300 to 5,100 ppm per gram of uncured resin tube.

2019, The Purdue University team published (Whelton et al., 2019) a Federal Highway Administration research report for the six state departments of transportation. An entire section of the report was dedicated to occupational safety issues and recommendations to reduce exposures.

2020, The Purdue University team published a peer-reviewed study (Sendesi et al., 2020) showing approximately 8.8% of the CIPP resin's initial weight was discharged into the air during CIPP heating. Because tons of CIPP resin is brought to each pipe repair site, roughly 6 to 32 tons of VOC – per CIPP project - is estimated to be deliberately discharged into the air in the field. The VOCs included HAPs, carcinogens, and chemicals with limited toxicology data available. Chemicals identified were styrene, styrene oxide, benzaldehyde, tetradecanol, 1,3,5-trimethylbenzene, *N*-propylbenzene, and others. Testing of new CIPPs also showed that they continue release styrene into the air even after ventilation as VOC residuals are left in the composites. Further, some of the 19 newly reported chemical exposure events (Supporting Information file) were inside nearby schools affecting teachers, in a cancer care center, and bakery.

2020, A CIPP industry group representing several large CIPP companies and Louisiana Tech University presented (Matthews et al., 2020) results of their field CIPP air testing study. Results showed 10s to 100s of ppm styrene was discharged into air through exhaust pipes at multiple worksites. A styrene level of 1,824 ppm was found exiting the uncured resin tube truck, which is where CIPP workers obtain the uncured resin tube to insert it into the buried pipe.

2020, The California Department of Health revised and reissued (California Department of Public Health, 2018) their statewide “Safety Alert” about the CIPP practice, waste discharge, and human exposure and health concerns.

2020, The Virginia Department of Health reported (Virginia Department of Health, 2020) CIPP installation practice and an interpretation of styrene health risk.

2020, The Florida Department of Health issued (Florida Department of Health, 2020) a statewide factsheet about CIPP for health officials about chemicals emitted, health symptoms, recommended medical support actions.

2021, A $3 million settlement was reached for a wrongful-death lawsuit brought on behalf of Brett Morrow’s family, the 21-year-old CIPP worker who died on a worksite in Streamwood, Illinois. The parties paying the settlement were Optimum Service Group Inc., Optimum Safety Management (Illinois-based company hired by Benchmark Construction to train its workers on safety procedures), Village of Streamwood [Infrastructure owner], JRG Materials, LLC [CIPP liner manufacturer], HR Green, Inc. [Engineering firm hired by Streamwood to consult on the project], and Benchmark Construction Company [CIPP installer].

2021, The NIOSH published (National Institute for Occupational Safety and Health, 2021) their first evaluation and recommendations about occupational chemical exposures during cured-in-place pipe liner preparation and during pipe repairs using hot water and steam curing practices. Results showed styrene exceeded worker safety thresholds.

2022, The Purdue University team published (Noh et al., 2022) a peer-reviewed study indicating emergency responder and public health considerations for chemical waste exposures in indoor environments. Some pressures applied by the CIPP contractor could lead to the blowback of sink and toilet water nearby residential buildings. Indoor contamination/decontamination simulation, based on the field measured literatures and incident reports, predicted that indoor air styrene exposure could exceeded public health threshold of 4.9 ppm.

SI-2. Additional supporting results

Proposal, conduct, and oversight of CIPP construction projects

The cured-in-place-pipe (CIPP) repair projects are contracted out by the infrastructure owner (i.e., municipality) to a CIPP company or subsidiary. City, county, utility, or state Department of Transportation agencies often request companies submit a proposal or bid that meets their requirements (i.e., construction specifications). Within the bid, the contractor often explains their proposed CIPP design, expected material performance, as well as onsite and post-construction actions. The contractor ultimately selected manufactures the new CIPP at a temporary worksite over a period of a few hours to days, depending on CIPP size, methods, and local conditions. The most common pipe diameters are 10.16 to 180 cm.

Common problems for plumbing fixtures

Chemicals can exit the uncured resin tube through a number of different pathways. High fluid pressures and hot curing temperatures can create pinholes and blisters in the CIPP wall (Ra et al., 2019), allowing liquids and vapors to pass through the uncured resin tube and enter nearby sewer laterals. Depending on field conditions, defects like irregular sewer lateral cutouts, folded or ripped liners, and holes can exist. CIPP industry standards encourage contractors to inject 3 to 15% v/v more resin than the CIPP needs for mechanical strength to compensate for resin volume change due to polymerization, thermal expansion/contraction, and resin *migration* out onto the host pipe. Uncured resin slugs in laterals also can be created, allowing chemicals to volatilize into sewer air after contractors leave worksites. Waste constituents also travel across the ground surface into public spaces and through building entry points, posing public health hazards (Noh et al., 2022; Ra et al., 2019; Sendesi et al., 2020; Teimouri Sendesi et al., 2017).

Separate from CIPP, the migration of gases from sewers into homes and other buildings is well known as a health concern. Several recent reports have established the sewer gas to indoor air pathway as an important to consider during vapor intrusion investigations (Jacobs et al., 2015; Pennell et al., 2013; Roghani et al., 2018). These studies (*which do not account for high-pressure conditions*) highlight challenges associated with characterizing the pathway, which is helpful for understanding CIPP exposure risks for indoor air spaces, even though some differences in sewer gas transport will exist between CIPP and hazardous waste vapor intrusion scenarios.

Vapor intrusion, the transport of hazardous chemicals from soil and/or groundwater into indoor spaces, is notoriously difficult to characterize, yet extremely low chemical concentrations in indoor air are health-relevant. In buildings where plumbing is appropriately installed, maintained, and verified as operating properly, sewer gas infiltration is unlikely. However, when traps and/or drains become dry, if joints and fittings are not properly working, or if piping runs separate or deteriorates, sewer chemicals can enter indoor spaces. The existence of improper or poorly maintained plumbing fixtures is common, including faulty traps, failing toilet seals (Pennell et al., 2013), disconnected roof vents, broken pipes/disconnected joints behind walls, or lose threaded joints. This allows sewer gas entry into the indoor air space. Even though the building plumbing may have been installed initially according to plumbing code, it is conceivable, and perhaps probable, that sewer gas as well as CIPP wastes could enter indoor air spaces and pose health concerns. Unique to CIPP however is that the contractors apply artificial pressure and plumbing, not meant for pressurization, can experience greater pressures than vapor intrusion conditions. Since less than 10 kPa can displace a typical p-trap water seal, nearby CIPP activities can displace water seals allowing chemical through plumbing (Noh et al., 2022). Numerous incidents of p-trap water seals being blown out prompting CIPP emissions to enter nearby buildings have occurred.

Other technical detection methods and biomarker studies that may affect exposure and health risks

It is well-known that biomarkers can be used for estimating human exposure to composite (VOC vapor) emissions (Edling et al., 1993; Liljelind et al., 2003; Persoons et al., 2018). However, these biomarkers have not been examined for complex CIPP waste exposures and may not be appropriate given the complexity of emissions. To establish these biomarkers, controlled laboratory evaluations are needed. These evaluations would require *in vivo* exposure models and screening of readily accessible biological fluids for identification and quantification of exposure and toxicity biomarkers. For instance, these laboratory-based studies could examine specific composite manufacturing practices that modify emissions, as well as biological responses. These biomarkers then could be validated in biological samples from individuals exposed to CIPP emissions. Numerous factors require examination to understand human health impacts of CIPP emission exposures including: 1) worksite factors contributing to variability in exposure concentrations and health responses, 2) identification of susceptible groups (e.g., individuals with respiratory diseases, young children, elderly, individuals with heightened sensitivity to chemicals), 3) evaluation of secondary exposures (i.e., production of ozone), 4) acute vs chronic exposure risks, 5) evaluation of toxicity mechanisms for the development of intervention/treatment strategies, and 6) the investigation of multiple matrixes (i.e., home, worksite, public spaces near worksites – playgrounds).

Based on field studies and authors' experiences, emergency responders and health officials have been advised not to rely on handheld photoionization detector (PID) devices for CIPP incident styrene investigations (Noh et al., 2022). Rapid air testing with PID is popular for CIPP companies, industrial hygiene firms, and emergency responders. Evidence however suggests that these devices over- and under-estimate styrene levels up to 1,000-fold compared to sorbent tube gas chromatography/mass spectrometry chemical quantification results (Najafi et al., 2018; National Institute for Occupational Safety and Health, 2019; Ra et al., 2019; Teimouri Sendesi et al., 2017). This was likely due to the complex atmosphere (multiple VOCs that prompted PID response). Some PID manufacturers purport to measure 0 to 15,000 ppm styrene vapor in real-time with instruments calibrated using 10 ppm of isobutylene standard (National Institute for Occupational Safety and Health, 2019). Previously, National Institute for Occupational Safety and Health (NIOSH) found some PID signals varied due to alterations in relative humidity, temperature, and other conditions for to cyclohexane vapor (Coffey et al., 2012; LeBouf & Coffey, 2015).

Various exposure scenarios that are likely in CIPP installation worksite

The classic cumulative risk challenge is lack of data, which includes all hazard factors. Effectively, no simple answers exist when considering the complexity of harms that can occur from single or multiple chemical exposures. Efforts to answer cumulative risk questions have fallen behind the impetus for only demonstrating the sole source apportionment of toxic response.

Example exposure scenarios that lack quantification evidence include: 1) uncured resin being removed from the delivery truck (National Institute for Occupational Safety and Health, 2021; Teimouri Sendesi et al., 2017); 2) uncured resin tube inserted and positioned inside the damaged pipe (Li et al., 2019); 3) excess resin seeping out of the CIPP into the sewer, does not harden (or cure) during CIPP manufacture and volatilizes into the air after contractors leave the worksite; 4) waste discharged into air and/or directed to an exhaust pipe(s) sometimes placed downstream (Matthews et al., 2020; National Institute for Occupational Safety and Health, 2019; National Institute for Occupational Safety and Health, 2021); 5) contractors cutting newly manufactured plastics (Li et al., 2019; National Institute for Occupational Safety and Health, 2019; National Institute for Occupational Safety and Health, 2021); 6) waste entering nearby buildings, and 7) after the new CIPP is placed into service.

Residential and community risks should be assessed in terms of the likelihood of exposure throughout the lifecycle of the CIPP installation and use. This action will require more data (i.e., breadth of emissions as well as understanding of vapor transport outdoors in sewers and plumbing). A better understanding of occupational risks could help understand public health risks by documenting direct emissions and material and operational conditions that prompt different chemical waste profiles. The same chemical analyses will be needed, but with specific concern of not incurring right-censored issues from the potentially higher concentrations that workers experience. While workers can move away from the waste exposure, publics inside buildings can be exposed when waste exhausts into buildings through drains, windows, doors mimicking confined spaces (i.e., small bathrooms, etc.).

Conceptual model of environmental health literacy for CIPP installation

In the conceptual model of environmental health literacy (EHL), Finn and O'Fallon (2017) posit that individuals and communities may demonstrate or require different levels of knowledge for different environmental health hazards and protective actions (Finn & O'Fallon, 2017). For example, some exposures can be avoided simply by recognizing the potential hazard that exists and applying that knowledge to avoid exposure. In a CIPP context, this might mean bystanders cross the street or take a different walking route upon seeing work underway. This is not possible for the building occupant or a sewer line. First responders, however, require more in-depth knowledge. For example, emergency management services need knowledge to address the hazard as it occurs, while workers should be adept at preventing emergencies.

Table S1. Comparison of manufacturing methods and materials

Resin types	Polyester	Vinyl ester	Epoxy
	Marks: Styrene is the most common CIPP resin compound. It used to be called "styrene resin" vs. "nonstyrene resin". Resin + solvents + fillers + catalysts + initiators are added to create an uncured resin tube		
Method to insert uncured resin tubes	Air inversion	Water inversion	Pull in place
	Marks: Sometimes resin may leave the tube and flow into cracks and sewer laterals. May not cure. Tubes sometimes have a plastic coating. Plastic "preliners" sometimes used.		
Method to polymerize	Thermal – steam injection	Thermal – hot water recirculation	UV – light exposure
Method to cooldown	Forced hot air	Forced ambient air	Recirculated water

Notes: ambient air CIPP curing rarely conducted.

Table S2. Chemical compounds found in air during/after CIPP manufacture and their potential health impacts

Purpose	Chemicals involved	Potential health effects
Initiator degradation products	Acetic acid, acetone, acetophenone^{HAP}, benzene$^{CAR, EDR, HAP}$, benzoic acid, 4-*tert*-butylcyclohexanol; 2-butatone; cumene$^{CAR, HAP}$; 1-tetradecanol	**Eyes,** skin, **nose, throat, mucous irritant**; **eye and skin burns**; **headaches**; **dizziness**; **nausea**; skin sensitization; dental erosion; black skin; hyperkeratosis, conjunctivitis; blurred vision; lacrimation; pharyngeal edema; central nervous system depression; staggered gait; anorexia; **lassitude**; **narcosis and coma**; bone marrow and red blood cells decrease; hypnotic or sedative effects; hematological effects; weakened pulse; dermatitis; chronic bronchitis; some potential carcinogens
Monomer oxidation product	Benzaldehyde ^{EDR}; ethyl benzene $^{EDR, HAP}$; phenylacetaldehyde; toluene $^{EDR, HAP}$	**Eyes,** skin, **nose, throat, mucous membrane, and respiratory system irritant**; **headache**; **dizziness and lightheadedness**; **tiredness and drowsiness**; reduced alertness; loss of reflexes; slow reaction; **difficulty sleeping**; dermatitis; **narcosis**; lack of coordination and vertigo
Resin solvent	Carbon disulfide ^{EDR}; cyclohexane; dimethyl acetamide^{CAR*}; dioxane$^{CAR, HAP}$; ethyl acetate; ethyl alcohol^{CAR}; n-hexane $^{EDR, HAP}$; isopentane; methylene chloride$^{CAR, EDR, HAP}$; 1,2,4-trimethylbenzene ^{EDR}	**Eyes,** skin, **throat, nose, respiratory system irritant**; **cough**; **dizziness**; **drowsiness**; **confusion**; **headache**; loss of muscle coordination; poor sleep; **lassitude**; **anxiety**; anorexia; **nausea**; **vomiting**; weight loss; anemia; depression; hallucinations; delusions; psychosis; giddiness; **fainting**; polyneuropathy; reproductive and teratogenic effects; Parkinson-like syndrome; dermatitis; ocular changes; coronary heart disease; gastritis; kidney and liver damage; jaundice; kidney failure; **narcosis and coma**; **eye and skin burns**; dermatitis; potential carcinogens
Plasticizers	Dibutyl phthalate $^{EDR, HAP}$; diethyl phthalate ^{EDR}; isopropenyl benzene; naphthalene$^{CAR, EDR, HAP}$;	**Eyes,** skin, **nose, throat, upper respiratory system**, stomach **irritant**; **headache**; **dizziness**; **confusion**; **lightheadedness**; **breathlessness**; **nausea**; lacrimation; neurological damage; possible polyneuropathy and vestibular dysfunction; hemolytic anemia; liver damage; pain; **numbness and lassitude**
Unknown	Carbon tetrachloride$^{CAR, EDR, HAP}$; chloroform$^{CAR, EDR, HAP}$; nonanal; Isopropyl alcohol^{CAR}	**Eyes, nose, throat,** skin **irritant**; central nervous system depression; **nausea**; **vomiting**; **headache**; **lassitude**; anesthesia; liver, kidney injury; enlarged liver; **drowsiness**; **dizziness** and dry cracking skin; mental dullness; loss of coordination; anticipated carcinogen
Antioxidant	2,6-Di-*tert*-butyl-*p*-cresol^{EDR}	**Eye,** skin **irritant**
Lubricant	Isopropyl palmitate^{EDR}	**Eyes,** skin **irritant**
Additives	1-pentanol; 1,3,5-trimethylbenzene^{EDR}	**Eyes, nose,** skin, **throat, respiratory system irritant**; **dizziness**; **headaches**; **confusion**; **lightheadedness**; loss of muscle coordination; **passing out**
Monomers	Phenol$^{EDR, HAP}$; styrene$^{CAR, EDR, HAP}$; tripropylene glycol diacrylate; xylene$^{EDR, HAP}$	**Eyes, nose, throat, respiratory irritant**; **dizziness**; **confusion**; skin sensitization; loss of muscle coordination; toxic if inhaled; suspected reproductive toxicity; suspected mutagenicity; damage to organs with prolonged exposure; anticipated carcinogen

Notes: Self-reported health symptoms from CIPP incidents are bolded for the chemicals confirmed present in CIPP air emissions. This health effects listed are from NIOSH (National Institute for Occupational Safety and Health, *2022)and CDC (Centers for Disease Control and Prevention, 2018), New Jersey Department of Health (New Jersey Department of Health, 1999, 2002, 2007, 2009), Santa Cruz Biotechnology (Santa Cruz Biotechnology, 2008, 2009, 2011, 2015), and Ashland^{TM} (Ashland, 2016); Abbreviations: CAR = carcinogenic compound; CAR*= Confirmed animal carcinogen with unknown relevance to humans, EDR = endocrine disruptors; HAP = hazardous air pollutant.*

Table S3. Knowledge-gaps identified in the literature for health risk assessment for CIPP waste in air

Category	Issues needed to be addressed
Exposure pathways and dynamics	Under what conditions are types of plumes being developed? How do these plumes behave – can we use standard methods? What is the amount of particulate resin and other components of the plume? How and to what concentration are the plumes entering buildings? How does the plume component that enters buildings behave in indoor air and deposit on surfaces with which chemicals persisting on those surfaces?
Dose-response	What are the single and cumulative exposure dose effects on cells, cellular systems and host outcomes?
Risk characterization	What are cumulative risks from the plume? Are different manufacturing practices producing different risks and sets of risks? What is the time series of risk from CIPP installation initiation to acceptably small risks to the population for the surrounding community? What is the radius of effect that can be expected for communities for outdoor air risks, and within buildings for residential and other indoor risks?

Table S4. Workgroup feedback and questions were prioritized by public health associations by topic

Issues/ Gaps	Prioritized Questions Based on Public Health Associations Representatives Votes among the Entire Feedback of Participants
Plastic CIPP Manufacture and Wastes	
Curing Technology	• Will CIPP use increase with potential upcoming infrastructure spending? • Does UV curing generate lower amounts of VOCs than steam/hot water? • What is the source for 70% of CIPP installations having defects and how these defects can affect VOC concentrations, amount of uncured resin in the exhaust? • Are there nonstyrene based products or alternatives for styrene products?
Generated Wastes	• PRIORITY #2: Do employers maintain accurate safety data sheets health departments can refer to? If not, is there a collection of current safety data sheets to review?
Measurement Technology	• If the photoionization detector (PID) does not give a good way to measure VOC concentration, then what would be a good way to collect/measure the concentration indoors? • Have employers measured airborne contaminants like styrene, methylene chloride?
Mitigation Technology	• PRIORITY #1: How can emissions be minimized? • Can emissions be captured? • If a GAC system is used to mitigate CIPP gas intrusion, how long would that need to be on site for a CIPP procedure?
Utility Practice	• PRIORITY #3: What is the distribution of CIPP events across the country? • Is there contract wording that utilities could use to minimize these issues? • Is there any region where this process is more widely used?
Sewers and Buildings	
Plumbing System	• PRIORITY #2: What kind of physical damage of plumbing do CIPP installation cause to? • PRIORITY #3: Could the CIPP VOC emissions in urban areas contribute enough to impact the attainment and non-attainment status?
VOC Pathways	• PRIORITY #1: How do vapors, including sewer gas and VOCs, move in sewer systems when not under pressure and during the CIPP process? • PRIORITY #2: Most of utility pipes are running down the street. How can it happen even though the installation time is short? Is it because of disrupted pipe impact? Or the exhaust fan leads the air flow from a worksite (high concentration) to indoor (low concentration)? • Should air districts be involved in CIPP projects?
Chemical Exposure and Health Effects	
Public Exposure	• PRIORITY #1: How can estimate the health effect? • PRIORITY #1: When CIPP is used to repair drinking water pipes, do chemicals leach out into the drinking water over time? • PRIORITY #3: What is its impact on the residential air and the surrounding area? • PRIORITY #3: What is the interaction and health impact between indoor air /air toxic and CIPP installation?
Occupational Exposure	• PRIORITY #2: What data exist regarding occupational exposure? • What are the acute versus chronic exposures?

Toxicity/ Health Effects	• PRIORITY #2: What CIPP emission components drive toxicity, beyond styrene? Perhaps simple mixtures of these compounds could be used in toxicological studies. • Can urinary styrene metabolites be monitored? Are there any other ways? • Do we have a good understanding of the physiological half-life of styrene? And other chemicals? • How would animal data vs. human data contribute to modeling?
Chemical Risk Assessment	
Emergency Management	• PRIORITY #1: Are municipalities required to notify residents about their intent to use this technology? This could help residents be aware of what they're being exposed to when it happens, and therefore help the health department providing the most relevant and timely information possible. Of the complaints we've received from residents, they typically do not know what CIPP was or was being used. • PRIORITY #2: What is the role of local emergency management in response?
Risk Assessment	• PRIORITY #1: In one state, they have risk assessors which perform work as a part of the APPLETREE program (related to CERCLA) which falls under the purview of the ATSDR; however, regarding occupational exposures we would refer these exposure instances to NIOSH to perform site investigations and risk assessments. • PRIORITY #2: In one state part of APPLETREE, they do risk assessments using ATSDR screening guidance and dose estimation. They do so for water and soil via drinking, showering, dermal contact for residents, leisure people, and workers. The model used is lacking air, but the state received guidance from ATSDR on how to evaluate air exposure. The state usually gets a request by any agency or county health department to do an assessment and needs to have environmental data provided to them. • At one state's local level, they do not do risk assessments with private entities. They would direct the company to work with a consultant. The agency may help other local entities help implement suggestions/findings.
Risk Communication	
Health Equity	• PRIORITY #3: Are there other health equity concerns? • Can there be a checklist to ensure public safety? • Is this practice used more frequently in certain socioeconomic level neighborhoods? • Do more affluent/privileged communities voice concern and receive more costly repairs to prevent exposure?
Incident Response	• PRIORITY #1: What is the best immediate health advice to provide to residents who contact the health department experiencing a vapor intrusion event? • PRIORITY #2: Are there steps people can take in their home to limit/minimize the vapor intrusion? • In one state, they had a recent case during the pandemic. When avoiding public spaces and practicing social distancing, what is the best advice to date? • Citizens who have been impacted are the most curious as to who is responsible for the exposure.

Notes: Some workgroup activities and questions were equally ranked by public health association in each category, so these were sometimes more than an item for a priority.

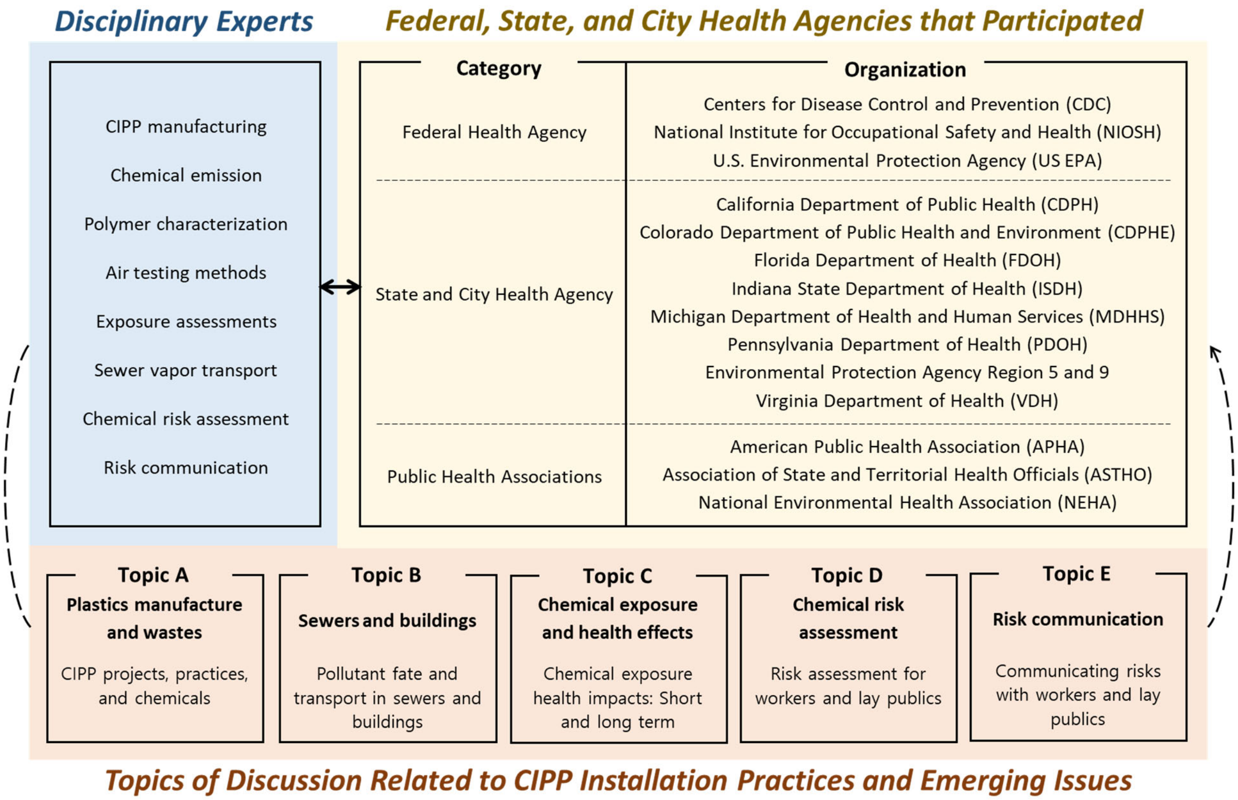

Figure S1. Diagram of workgroup formation and virtual activity organization

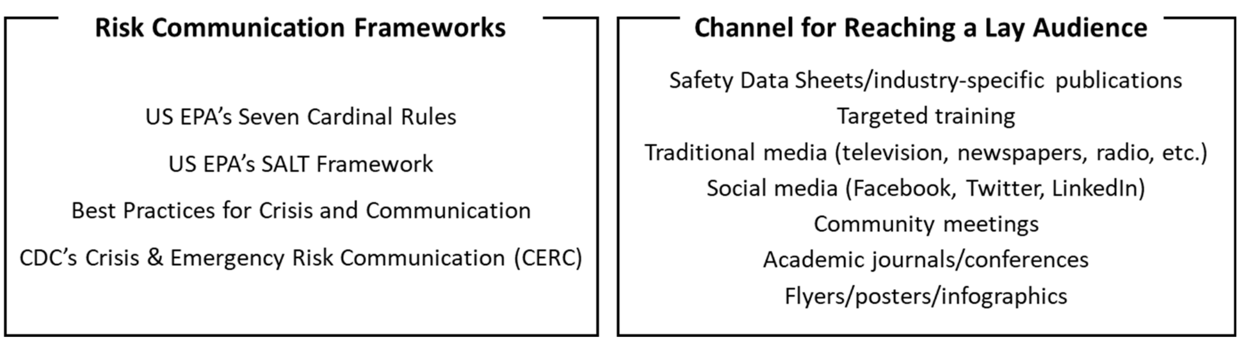

Figure S2. Risk communication frameworks can help diagnose communicative challenges, identify critical information needs, develop audience targeting strategies, and identify appropriate communication channels.

References

Ajdari, E.B. (2016). Volatile organic compound (VOC) emission during cured-in-place-pipe (CIPP) sewer pipe rehabilitation. University of New Orleans, New Orleans, LA.

Ashland™. (2016). *Tripropylene glycol diacrylate*. Wilmington, DE. Available at https://www.ashland.com/file_source/Ashland/Documents/Sustainability/rc_tripropylene_gylcol_diacrylate_pss.pdf.

Centers for Disease Control and Prevention (2018). *Emergency Preparedness and Response: Chemical Emergencies*. Atlanta, GA. Available at https://emergency.cdc.gov/chemical/index.asp.

Coffey, C., LeBouf, R., Lee, L., Slaven, J., & Martin, S. (2012). Effect of calibration and environmental condition on the performance of direct-reading organic vapor monitors. *J. Occup. Environ. Hyg.* 9(11), 670-680. doi: 10.1080/15459624.2012.725015.

Edling, C., Anundi, H., Johanson, G., & Nilsson, K. (1993). Increase in neuropsychiatric symptoms after occupational exposure to low levels of styrene. *Occup. Environ. Med.* 50(9), 843-850. doi:10.1136/oem.50.9.843.

Public Health England (2013). *Chemical Hazards and Poisons Report*. London, UK. Available at https://www.gov.uk/government/collections/chemical-hazards-and-poisons-reports.

Finn, S., & O'Fallon, L. (2017). The emergence of environmental health literacy—from its roots to its future potential. *Environ. Health Perspect.* 125(4), 495-501. doi: 10.1289/ehp.1409337.

California Department of Public Health. (2017). *Cured-In-Place-Pipe (CIPP) Additional Consideration for Municipalities*. Sacramento, CA.

California Department of Public Health. (2018). *CIPP Safety Alert*. Sacramento, CA.

Florida Department of Public Health. (2020). Cured-In-Place-Pipe [CIPP]. Marriottsville, MD. Available at http://www.floridahealth.gov/environmental-health/hazardous-waste-sites/_documents/final_fdoh_cipp.pdf.

Health, V. D. o. (2020). Styrene. *Access on. August 2020*, *https://www.vdh.virginia.gov/environmental-health/styrene/*.

Jacobs, J., Jacobs, O., & Pennell, K.G. (2015). One alternate exposure pathway of VOC vapors from contaminated subsurface environments into indoor air–legacy sewer plumbing systems. Feature article in the spring 2015 Groundwater Resources Association of California (GRAC) Newsletter, 20-24.

Kobos, L., Teimouri Sendesi, S.M., Whelton, A.J., Boor, B.E., Howarter, J.A., & Shannahan, J. (2019). In vitro toxicity assessment of emitted materials collected during the manufacture of water pipe plastic linings. *Inhal. Toxicol*. 1-16. doi:10.1080/08958378.2019.1621966.

LeBouf, R. F., & Coffey, C. C. (2015). Effect of interferents on the performance of direct-reading organic vapor monitors. *J. Air Waste Manag. Assoc*. 65(3), 261-269. doi: 10.1080/10962247.2014.986308.

Li, X., Ra, K., Nuruddin, M., Sendesi, S.M.T., Howarter, J.A., Youngblood, J.P., Zyakina, N., Jafvert, C.T., & Whelton, A.J. (2019). Outdoor manufacture of UV-Cured plastic linings for storm water culvert repair: Chemical emissions and residual. *Environ. Pollut*. 245, 1031-1040. doi:10.1016/j.envpol.2018.10.080.

Liljelind, I., Rappaport, S., Eriksson, K., Andersson, J., Bergdahl, I., Sunesson, A., & Järvholm, B. (2003). Exposure assessment of monoterpenes and styrene: a comparison of air sampling and biomonitoring. *Occup. Environ. Med.* 60(8), 599-603. doi:10.1136/oem.60.8.599.

Matthews, E., Matthews, J., Alam, S., & Eklund, S. (2020) NASSCO CIPP Emissions Phase 2: Evaluation of Air Emissions from Polyester Resin CIPP with Steam Cure. Final Report for National Association of Sewer Service Companies, Inc. (NASSCO, Inc.). Louisiana Tech University, Ruston, LA.

Najafi, M., Sattler, M., Schug, K., Kaushal, V., & Iyer, G. (2018). Evaluation of Potential Release of Organic Chemicals in the Steam Exhaust and Other Release Points during Pipe Rehabilitation Using the Trenchless Cured-In-Place Pipe (CIPP) Method. Final Report. Prepared for NASSCO, Inc. Marriottsville, MD.

New Jersey Department of Health. (1999). *Hazardous Substance Fact Sheet_Isopropenyl benzene*. Trenton, NJ. Available at https://nj.gov/health/eoh/rtkweb/documents/fs/1072.pdf

New Jersey Department of Health. (2002). *Hazardous substance fact sheet_Benzaldehyde*. Trenton, NJ. Available at https://nj.gov/health/eoh/rtkweb/documents/fs/0196.pdf.

New Jersey Department of Health. (2007). *Hazardous Substance Fact Sheet_Amyl Alcohol*. Trenton, NJ. Available at https://www.nj.gov/health/eoh/rtkweb/documents/fs/0124.pdf.

New Jersey Department of Health. (2009). *Hazardous Substance Fact Sheet_Benzoic acid*. Trenton, NJ. Available at https://www.nj.gov/health/eoh/rtkweb/documents/fs/0209.pdf.

National Institute for Occupational Safety and Health. (2019). *Health Hazard Evaluation Report: Evaluation of Exposures to Styrene During Ultraviolet Cured-in-Place-Pipe Installation.* U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH, HHE Report No. 2018-0009-3334. Morgantown, WV.

National Institute for Occupational Safety and Health. (2021). *Evaluation of Exposures to Styrene during Cured-in-place Pipe Liner Preparation and during Pipe Repairs using Hot Water and Steam*. Report No. 2019-0080-3379. Morgantown, WV. Available at https://www.cdc.gov/niosh/hhe/reports/pdfs/2019-0080-3379.pdf.

National Institute for Occupational Safety and Health (2022). *NIOSH Pocket Guide to Chemical Hazards*. Available at https://www.cdc.gov/niosh/npg/npgsyn-a.html.

Noh, Y., Boor, B.E., Shannahan, J.H., Troy, C.D., Jafvert, C.T., & Whelton, A.J. (2022). Emergency responder and public health considerations for plastic sewer lining chemical waste exposures in indoor environments. *J. Hazard. Mater*. 422, 126832. doi: 10.1016/j.jhazmat.2021.126832.

Occupational Safety and Health Administration. (2018). *Citation and Notification of Penalty. Inspection Number 1274028* U.S., Department of Labor. Des Plaines, IL. Available at https://engineering.purdue.edu/CIPPSafety/resources/OSHA-Region5-CIPP-Fatality-Notification-of-Penalty-2018.pdf.

Pennell, K.G., Scammell, M.K., McClean, M.D., Ames, J., Weldon, B., Friguglietti, L., Suuberg, E.M., Shen, R., Indeglia, P.A., & Heiger-Bernays, W.J. (2013). Sewer gas: an indoor air source of PCE to consider during vapor intrusion investigations. *Ground Water Monit. Remediat*. 33(3), 119-126. doi:10.1111/gwmr.12021.

U.S. Federal Court District of Pennsylvania. (2018). *LABOR READY NORTHEAST, INC. v. WORKERS'COMPENSATION APPEAL BOARD*. Philadelphia, PA. Available at https://scholar.google.com/scholar_case?case=3514256982438106581&q=Pennsylvania+compensation+styrene+unconsious&hl=en&as_sdt=4,39.

Persoons, R., Richard, J., Herve, C., Montlevier, S., Marques, M., & Maitre, A. (2018). Biomonitoring of styrene occupational exposures: biomarkers and determinants. *Toxicol. Lett.* 298, 99-105. doi:10.1016/j.toxlet.2018.06.1211.

Ra, K., Teimouri Sendesi, S.M., Howarter, J.A., Jafvert, C.T., Donaldson, B.M., & Whelton, A.J. (2018). Critical Review: Surface Water and Stormwater Quality Impacts of Cured-In-Place Pipe Repairs. *J. Am. Water Works Assoc.* 110(5), 15-32. doi:10.1021/acs.estlett.7b00237.

Ra, K., Sendesi, S.M.T., Nuruddin, M., Zyaykina, N.N., Conkling, E.N., Boor, B.E., Jafvert, C.T., Howarter, J.A., Youngblood, J.P., & Whelton, A.J. (2019). Considerations for emission monitoring and liner analysis of thermally manufactured sewer cured-in-place-pipes (CIPP). *J. Hazard. Mater*. 371, 540-549. doi:10.1016/j.jhazmat.2019.02.097.

Agency for Toxic Substances and Disease Registry. (2005). *Health Consultation. Division of Health Assessment and Consultation. Health Consultation, Schlitz Park Office Building*. Milwaukee, WI.

RIVM (Rijksinstituut voor Volksgezondheid en Milie, Netherlands National Institute for Public Health and the Environment). (2006). *Sewer renovation with stocking methods: backgrounds in the information sheet, Report Number 609021038/2006.* Amsterdam, NED.

Roghani, M., Jacobs, O.P., Miller, A., Willett, E.J., Jacobs, J.A., Viteri, C.R., Shirazi, E., & Pennell, K.G. (2018). Occurrence of chlorinated volatile organic compounds (VOCs) in a sanitary sewer system: Implications for assessing vapor intrusion alternative pathways. *Sci. Total Environ*. 616, 1149-1162. doi:10.1016/j.scitotenv.2017.10.205.

Santa Cruz Biotechnology, Inc. (2008). *Safety Data Sheet_1-Tetradecanol*. Dallas, TX. Available at https://datasheets.scbt.com/sc-213413.pdf.

Santa Cruz Biotechnology, Inc. (2009). *Phenylacetaldehyde.* Dallas, TX. Available at https://datasheets.scbt.com/sc-250699.pdf.

Santa Cruz Biotechnology, Inc. (2011). *Safety Data Sheet_Isopropyl palmitate.* Dallas, TX. Available at https://datasheets.scbt.com/sc-250200.pdf

Santa Cruz Biotechnology, Inc. (2015). *Safety Data Sheet_4-tert-Butylcyclohexanol*. Dallas, TX. Available at https://datasheets.scbt.com/sds/wpna/en/sc-226796.pdf.

Tabor, M.L., Newman, D., & Whelton, A.J. (2014). Stormwater Chemical Contamination Caused by Cured-in-Place Pipe (CIPP) Infrastructure Rehabilitation Activities. *Environ. Sci. Technol.,* 2014; 48(18), 10938-10947. doi: 10.1021/es5018637.

Teimouri Sendesi, S.M., Ra, K., Conkling, E.N., Boor, B.E., Nuruddin, M., Howarter, J.A., Youngblood, J.P., Kobos, L.M., Shannahan, J.H., Jafvert, C.T., & Whelton, A.J. (2017). Worksite chemical air emissions and worker exposure during sanitary sewer and stormwater pipe rehabilitation using cured-in-place-pipe (CIPP). *Environ. Sci. Technol. Lett.* 4(8), 325-333. doi:10.1021/acs.estlett.7b00237.

U.S. Federal Court District of Kansas. (2018, June 12). *ROBERT LOGUE, Plaintiff, v. LAYNE INLINER, LLC, Defendant. Case No. 6:17-CV-01245-EFM-GEB*. 2018. Kansas City, KS. Available at https://scholar.google.com/scholar_case?case=14098124604562578481&q=sewer+lining+injury&hl=en&as_sdt=800006&as_ylo=2017.

Whelton, A.J., Ra, K., Teimouri Sendesi, S. M., Nuruddin, M., Li, X., Howarter, J.A., Youngbolood, J.P., Jafvert, C.T., & Zyaykina, N.N. (2019). Contaminant Release from Storm Water Culvert Rehabilitation Technologies: Understanding Implications to the Environment and Long-Term Material Integrity. U.S. Federal Highway Administration Transportation Pooled Fund (TPF)-5(339). West Lafayette, IN: Purdue University. doi:10.5703/1288284317089.